METHOD AND DEVICE FOR CARRIER RECOVERY IN OFDM SYSTEMS

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This application is based on and claims the benefit of Italian Patent Application No. MI2000A001589 filed on July 14, 2000, which is incorporated by reference herein.

BACKGROUND OF THE INVENTION

1. Field Of The Invention

The present invention generally relates to the use of OFDM (Orthogonal Frequency Division Multiplexing) technique and in particular relates to the use of such a technique for microwave point-to-point radio links. Still more in particular it relates to a method and device for carrier recovery in such OFDM systems at high working frequency.

2. Description Of The Prior Art

The availability on the market of large scale integration electronic components in recent years has allowed the use of OFDM techniques in several fields, among which the DVB (Digital Video Broadcasting) standards for the VHF-UHF terrestrial television broadcasting and DAB (Digital Audio Broadcasting) standard for the transmission of the audio signal. As it is known, the OFDM modulation technique consists in transmitting several flanked orthogonal carriers. The main reason for which this type of modulation has been selected during

standardization to simple-carrier systems is due to the inherent robustness to distortions which are on the terrestrial channel because of the multipath phenomenon.

The frequency multiplexing with orthogonal carriers is the winning characteristic of the OFDM system but, just for this reason, such orthogonality must be absolutely kept in order to have the correct operation of the system itself.

The OFDM modulation proves to be particularly weak towards the carrier synchronism errors, namely, the performances quickly degrade even for small frequency offsets. It is then necessary to guarantee that the system always operates under locking conditions, and quickly corrects possible sudden frequency offsets (clicks) caused by local oscillators (OLs) in transmission or in reception. It is in fact known that this phenomenon becomes more and more critical as the frequency of the OLs increases, because of an increasing implementation difficulty.

Since, so far, the OFDM modulation has been used in DAB or DVB systems, because the working frequencies are rather low, the phenomenon of the frequency clicks has been neglected in a first approximation. However, in view of a use of the OFDM technique at high frequencies, in particular for microwave point-to-point radio links, namely with working frequencies between 4 and 30 GHz, it is necessary to cope with said frequency click phenomenon.

SUMMARY OF THE INVENTION

The main object of the present invention is therefore to provide an effective method and device for the correction of the phase error caused by such frequency clicks, by using pilot symbols which are known at the receiver.

This and further objects are achieved by a method and device having the characteristics set forth in the independent claims 1 and 9, respectively. Further

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advantageous characteristics of the methods and device are set forth in the respective dependent claims. All the claims are intended to be an integral part of the present description.

The basic idea of the present invention consists in arranging, in a contiguous manner, pilot carriers inside the transmission data flow so that, when properly extracted in the receive data flow through a band-pass filtering, can be used for a feed-forward correction of the phase error to be carried out before computing the Discrete Fourier Transform (DFT).

There now follows a detailed description of the invention, provided by way of a mere non limiting example, to be read with reference to the attached drawing sheets.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

- Fig. 1 shows a basic schematic representation of a known OFDM modulator transmission side;

- Fig. 2 shows a block diagram of the OFDM modulator of Fig. 1;

- Fig. 3 shows a block diagram of a first embodiment of the receiver according to the present invention;

- Fig. 4 shows a block diagram of a second embodiment of the receiver according to the present invention; and

- Fig. 5 shows a diagram representing the sampling and the piecewise linear interpolation of the phase ϕ.

BEST MODE FOR CARRYING OUT THE INVENTION

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Before describing the characteristic features of the present invention, it is believed to be useful to briefly mention in greater detail some aspects of the OFDM modulation technique.

The OFDM technique consists in generating a set of spectra, partially overlapped and orthogonal to each other, of the type sin(x)/(x) in the frequency domain and of rectangular pulses in the time domain, correspondingly. It is a multitone system taking benefit from the fact that the signal to be transmitted is generated by Fourier Transform that combines modulation, multiplexing and pulse shaping into a single operation.

Each carrier is modulated according to a fixed constellation ,chosen from the xPSK or xQAM family (for instance QPSK, 16QAM, 64 QAM, etc.., depending on the characteristics of the channel). The bit sequence (BS) coming into the OFDM modulator is subdivided, at each time interval T_S, into N m-bit blocks; a complex number $X_{i,k}$ is associated with each block, the complex number representing a symbol of the constellation that has been chosen. Once a bit string has been mapped into a symbol sequence, each symbol is associated with one of the subcarriers so that a vector of N sequential symbols will correspond to a system of N different carriers. The sum of the carriers constitutes the signal $x_i(t)$ associated with the so-called OFDM symbol and that can be qualitatively represented as:

$$x_i(t) = \sum_{k=0}^{N-1} X_{i,k} e^{j2\pi f_k t} rect_{T_S}(t - iT_s)$$

The overall signal $x(t)$ is given by the sum of the transmitted OFDM symbols $x_i(t)$, according to the following relation:

$$x(t) = \sum_{i=-\infty}^{+\infty} x_i(t) = \sum_{i=-\infty}^{+\infty}\sum_{k=0}^{N-1} X_{i,k} e^{j2\pi f_k t} rect_{T_S}(t - iT_s)$$

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In order to reduce the spectral occupancy, it is necessary for the carriers to be orthogonal with each other and namely that their scalar product is identically equal to zero, or that they hence satisfy the following analytic condition:

$$\int_0^T e^{j2\pi f_k t} e^{j2\pi f_h t} dt = 0 \text{ per } h \neq k$$

This results in that the frequencies of the carriers are chosen equal to integer multiples of the reciprocal of the duration T_S:

$$f_k = f_0 + \frac{k - N/2}{T_S} \qquad k = 0, \cdots, N-1$$

f_0 being the central carrier frequency.

The signal so obtained is sampled with sampling interval $T = T_S/N$, N being the number of carriers. The signal $x(nT)$ that is obtained is therefore:

$$x(nT) = \sum_{i=-\infty}^{+\infty} \sum_{k=0}^{N-1} X_{i,k} e^{j2\pi kn/K} rect_{T_S}(nT_S/N - iT_s)$$

There is now the need to pass on to analog signals. The digital-to-analog conversion of these samples instead generates a continuous signal that will modulate a radio frequency carrier. It will be appreciated that the above expression is equivalent to an inverse discrete Fourier transform (IDFT) of the complex coefficients $X_{i,k}$ except for a factor 1/N. This suggests a way for practically implementing the OFDM modulation: in transmission, an IDFT of the symbols $X_{i,k}$ is carried out while in reception the inverse operation, namely a discrete Fourier transform (or DFT), will be performed.

Hence, taken a vector N of complex symbols to be transmitted, N samples x_n of the OFDM symbol will be transmitted, with:

$$\{x_{i,n}\} = IDFT\{X_{i,k}\}$$

or

$$\{x_{i,n}\} = \frac{1}{N}\sum_{k=0}^{N-1} X_{i,k} e^{+j\frac{2\pi}{N}kn}$$

whereas in reception

$$DFT\{x_{i,n}\} = \{X_{i,k}\}$$

In case of intersymbol interference caused by the transmission channel, the orthogonality properties between the signals can fail. Inside the time T_S that is available for transmitting the OFDM symbol, a guard time T_g is derived so that the echoes, or signal reflections, that in reception fall inside this interval are used in a constructive manner in order to restore the main signal. Hence we will have:

$$T_S = T_u + T_g$$

where T_u is the usable portion of the transmitted signal (equal to $N \cdot T$), T_g is the guard time, T_S is the total duration of the transmitted OFDM symbol; and T is the time associated with a QAM symbol.

Moreover, the OFDM signal so defined can use part of the available carriers, called pilot carriers, to transmit symbols that are known to the receiver, to be able to perform the channel equalization or to restore the symbol or carriers synchronization.

Figs. 1 and 2 respectively represent a basic diagram of the OFDM signal generation and the main functional block diagrams forming the modulator. The stored bit sequence (BS) to be transmitted is subdivided into N blocks, with each block having m bits (for instance, m=6 for a constellation of symbols chosen from the 64 QAM family). The bit blocks enter coding and mapping blocks (C&M) where, associated with each of them is a symbol of the constellation. Then they are multiplied by the various carriers $f_1, f_2, ..., f_N$ (namely, each symbol is associated with a carrier). Block D/A is an analog to digital converter that converts a signal obtained

from the sum of the various carriers multiplied by the corresponding coded information.

In practice, it is stressed that the diagram of Fig. 1 depicts how the OFDM signal is theoretically generated; but in fact it is generated by means of a chip (see IFFT block in Fig. 2), easily available on the market, capable of performing the same operation in significantly restricted spaces with higher speed and reliability. In Fig. 2, FA designates a frame adaptation block for the data handling (FA receives at its input the QAM complex symbol); S/P is a block that carries out a serial-to-parallel conversion; IFFT is a signal generation block that performs a fast Fourier transform; and GI is a guard insertion block.

The frequency click effect (Δf) on the OFDM signal is of two types: on one side, it results in a phase rotation for every symbol, on the other side it results in a loss of orthogonality between the carriers in the same symbol that therefore interfere with one another. This latter aspect, typical of the OFDM modulation, is the one that makes the problem of the carrier synchronization much more critical as compared with the case of a single carrier system.

It can be proved that the effect of a frequency click Δf is:

$$\left\{ z_{i,n} \right\} = \left\{ \sum_{k=0}^{N-1} e^{+j\pi(N-1)\Delta fT} \frac{\sin(\pi N\Delta fT)}{N\sin(\pi\Delta fT)} X_{i,k} + I(n) \right\}$$

Therefore, the effects of a frequency click are two: i) a reduction in the symbol amplitude by a factor equal to $\dfrac{\sin(\pi N\Delta fT)}{\sin(\pi\Delta fT)}$, and ii) introduction of a sort of inter symbol interference due to the loss of orthogonality of the carriers.

In view of such considerations, the present invention provides for carrying out the phase error correction at reception side, before performing the DFT operation. On the contrary case, the DFT operator would require to wait for the reception of all the

N transmitted samples before being able to start the computation of the transform, thus introducing an unacceptable delay for the phase correction.

In addition to the above, as already said, the basic idea of the present invention consists in arranging pilot carriers in a contiguous manner inside the transmission data flow. Such "flanked" pilot carriers, properly extracted from the receive data flow through a band-pass filtering, are then used for a feed-forward correction of the phase error, to be carried out before performing the DFT.

The sequence $\{x_{i,n}\}$ to be transmitted, taken at the input of the analog to digital converter, will then be given by:

$$\{x_{i,n}\} = \frac{1}{N} \left\{ \sum_{k=0}^{k_1-1} X_{i,k} e^{+j\frac{2\pi}{N}kn} + \sum_{k=k_1}^{k_2} A_k e^{+j\frac{2\pi}{N}kn} + \sum_{k=k_2+1}^{N-1} X_{i,k} e^{+j\frac{2\pi}{N}kn} \right\}$$

with $k_1, k_2 \in [0, N-1]$ and where A_k are the xQAM symbols associated with the pilot carriers, i.e. symbols known to the receiver, and $X_{i,k}$ are the xQAM symbols associated with the carriers containing the information to be transmitted.

With reference to Fig. 3, the received signal $\{\tilde{x}_{i,n}\}$ that, considering an ideal channel, can be held to be equal to $\{x_{i,n}\}$, is properly band-pass filtered (FBP) in order to isolate the pilot carriers, obtaining a signal $y_p(n)$. For instance, an ideal band-pass filtering, adapted to the pilot carriers (having pass band centered on the pilot block), can be performed.

A complex conjugate operation (see block CONJ) is performed on the signal $y_p(n)$, thus obtaining a signal $y_p^*(n)$.

The signal $y_p^*(n)$ is multiplied by a local replica of the pilot symbols, namely

by $p(n) = \frac{1}{N} \left\{ \sum_{k=k_1}^{k_2} A_k e^{+j\frac{2\pi}{N}kn} \right\}$, generating a signal $s(n)$.

The information on the phase of the signal $s(n)$ is then extracted through a block that, upon receipt of a vector at its input, calculates the unit vector related thereto by dividing every sample by its module and outputting a signal of the type $e^{+j\phi(n)}$.

The correction is performed by multiplying the received signal $\{\tilde{x}_n\}$ by the signal $e^{+j\phi(n)}$ that was generated as indicated above.

Lets consider now, by way of a non limiting example, the presence of a frequency click Δf occurring at the instant n_τ (with $0 \le n_\tau \le N-1$). The received signal $\{\tilde{x}_{i,n}\}$ will be:

$$\tilde{x}_{i,n} = \begin{cases} x_{i,n} & n < n_\tau \\ e^{+j2\pi\Delta f(n-n_\tau)} \cdot x_{i,n} & n \ge n_\tau \end{cases}$$

The output of the band-pass filter FPB (still in the ideal case) and except for an unessential multiplication factor $\dfrac{1}{N^2}$ will be:

$$y_p(n) = \begin{cases} \displaystyle\sum_{k=k_1}^{k_2} A_k e^{+j\frac{2\pi}{N}kn} & n < n_\tau \\ e^{+j2\pi\Delta f(n-n_\tau)T} \cdot \displaystyle\sum_{k=k_1}^{k_2} G_k A_k e^{+j\frac{2\pi}{N}kn} & n \ge n_\tau \end{cases}$$

where G_k is a term that depends on the way the filtering is realized and on the frequency click which is present. Obviously, for adapted filtering and Δf null, it follows $G_k = 1$ for every K, whereas at the opposite end for Δf greater than $(k_2 - k_1)/T$ one will have $G_k = 0$.

The multiplication of the locally generated pilot signal $p(n)$ and signal $y_p^*(n)$ gives the following signal as a result:

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$$s(n) = \begin{cases} \left\{ \displaystyle\sum_{k=k_1}^{k_2} A_k e^{+j\frac{2\pi}{N}kn} \right\} \cdot \left\{ \displaystyle\sum_{k=k_1}^{k_2} A_k^* e^{-j\frac{2\pi}{N}kn} \right\} & n < n_\tau \\[2em] e^{-j2\pi\Delta f(n-n_\tau)T} \cdot \left\{ \displaystyle\sum_{k=k_1}^{k_2} A_k e^{+j\frac{2\pi}{N}kn} \right\} \cdot \left\{ \displaystyle\sum_{k=k_1}^{k_2} G_k A_k^* e^{-j\frac{2\pi}{N}kn} \right\} & n \geq n_\tau \end{cases}$$

In the first term, the product will be real, whereas in the second term there is a phase proportional to the click amplitude.

Considering the associated unit vector, one obtains that

$$e^{+j\phi(n)} = \begin{cases} 1 & n < n_\tau \\ e^{-j2\pi\Delta f(n-n_\tau)T} + I(n) & n \geq n_\tau \end{cases}$$

$I(n)$ being a generic disturbance term that takes into account the fact that, in case of clicks and/or non ideal filterings, it is not assured that $G_k = 1$ for every k. The term $I(n)$ is a generic distortion that can be anyway considered negligible provided that the quantity $k_2 - k_1$, i.e. the number of pilot carriers, is not significantly low.

The signal $e^{+j\phi(n)}$ must be then multiplied by the received signal $\{\tilde{x}_{i,n}\}$, correcting the phase error introduced by the frequency click. An FFT is then performed on the signal so obtained and the result is sent to the decision circuit (not shown).

A second embodiment of the carrier recovery device according to the present invention is shown in Fig. 4. The difference consists in the steps of subsampling the phase $\phi(n)$ and in performing a piecewise linear interpolation between the various phase estimates. With reference to Fig. 4, let $\phi_1(nT)$ be the phase information (PHEXT) extracted from $\phi(nT)$ after a proper unwrapping operation and let $\phi_1(nT')$ be a subsampled replica thereof (PHEST) with $T' = pT$, p being a non-zero integer. At this point it is possible to perform a piecewise linear interpolation, according to the basic diagram illustrated in Fig. 5, between two subsequent phase estimates, e.g. $\phi_1(nT')$ and $\phi_1((n+1)T')$, to obtain $\phi_1(nT)$.

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According to the invention, all the pilot carriers are located in contiguous positions. However they can be used for a channel estimation, if the channel is slowly variable, as it is the one for the point-to-point radio links, thus shifting, at every OFDM symbol, the portion of spectrum reserved to the pilot carriers.

At this point it will be understood how the transmitter device for implementing the present invention is practically unchanged as compared with the known devices, apart from the mapping means (C&M).

It is apparent that several modifications and adaptations can be imparted to the present invention without departing from the scope defined by the following claims which are intended to be an integral part of the present description.